Climate Change Impacts and Adaptation in California

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Abstract

This paper presents a short review of the existing literature on climate change impacts and adaptation options for California. At the global scale, there is a scientific consensus that climate is changing and that the increased concentration of greenhouses gases in the atmosphere are responsible for these changes. California will get warmer in the future, but the level of warming is not known.

With respect to precipitation, there is no consensus on how California would be affected, but it is clear that the warming would result in increased runoff in the winter season and decreased runoff in the spring and summer. Human adaptation to climate change in the state may be costly. Ecosystems, one of the most precious state resources, could be severely affected not only by climate change, but also by other stressors such as increased urbanization.

Because of the thermal inertia of the Earth, our climate will continue to warm and, for this reason, the identification of adaptation options should be a state priority. Finally, this paper suggests that scientific research should be an integral part of the state overall strategy for how to deal with climate change.

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1. Introduction

The scientific community has reached consensus that global climate change due to human activities is real and that it could severely affect the world's natural ecosystems and economies. At the California level, although there is still considerable uncertainty about certain elements and regional details (such as of the impact of anthropogenic climate change on precipitation), changes in other elements (such as warmer temperatures and higher sea levels) appear quite certain. A number of recent scientific studies have concluded that climate change has the potential to affect every sector of the state's economy.

In its last assessment in 2001, the Intergovernmental Panel on Climate Change (IPCC), an international scientific body mandated to periodically summarize the state of the climate change science, concluded that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[1] In May 2001, President George W. Bush asked the National Academy of Science (NAS) to assess the veracity of the IPCC findings.

According to the NAS, the 2001 IPCC assessment "accurately reflects the current thinking of the scientific community on this issue." In addition, according to the report submitted by the NAS to the White House, "greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. Temperatures are, in fact, rising."[2]

The NAS also has warned that abrupt climate changes have occurred in the past several thousand years, when external forces affected the climate system. "Thus, greenhouse warming and other human alterations of the earth system may increase the possibility of large, abrupt, and unwelcome regional or global climatic events."[3]

Within this overall context, this paper contains a non-exhaustive critical review of major California-relevant scientific findings. Much of this information is based on the results of recently completed reports for the California Energy Commission's Public Interest Energy Research (PIER) Program and peer-reviewed scientific papers. The goals of the paper are: (1) to summarize the scientific literature in a format that informs policy without advocating any positions and (2) to provide a brief overview of the relevant research agenda.

2. Global Climate Change

Since the publication of the IPCC Third Assessment Report (TAR) in 2001, researchers have made significant progress on the science of climate change detection and attribution. In the past, most of the studies that sought to detect a climate change signal were focused on surface air temperature observations. Scientists have now expanded this detection effort by comparing several aspects of observed historical trends with those predicted by numerical climate model runs, including both the earth's surface as well as in different levels in the atmosphere and the ocean.

In the atmosphere, researchers have identified different trends in surface temperature and surface pressure in different parts of the world,[4] and increases of the tropopause (the boundary between the troposphere and stratosphere) height. These changes are unlikely to be the result of natural variability, and they are consistent with theoretical understanding of how climate change would affect these parameters. In fact, these observations are in agreement with model simulations *only* when the models are forced by the observed increased concentration of greenhouse gases (GHGs).[5, 6]

The world's oceans are absorbing approximately 84 percent of the total increase of heat on the earth's system.[7] The observed large-scale warming of the oceans closely matches the geographically differentiated warming and the vertical distribution of heat that scientists predict, using a state-of-the-art global climate model driven by the observed increase of GHGs in the atmosphere. Absent this forcing, the model was again unable to duplicate the observed pattern of warming—implying that the likelihood that natural causes produced this warming is very remote.[8, 9]

These new scientific findings provide strong evidence for the "fingerprints" of human-induced climate change, providing additional support to the assertion that climate change is already detectable and that these changes are attributable to anthropogenic forcing. Looking forward, the following subsections present information on the climatic changes that could be expected in the future and the role that society may have in minimizing these changes.

Global Climate Scenarios

Greenhouse gases are accumulating in the atmosphere as a result of human activities, such as the combustion of fossil fuels and the deforestation of large regions in the world.

According to the 2001 IPCC TAR report, our planet has warmed between 0.4 and 0.8 degrees Celsius, ºC (0.7 and 1.5 degrees Fahrenheit, ºF) in the twentieth century and sea level has increased by about 0.15 meters (0.5 feet).[1] The IPCC estimates that global average temperatures could increase by 1.4ºC to 5.8ºC

(2.5ºF to 10.4ºF) by 2100 and that the sea level may rise from 0.09 meters to 0.88 meters (0.3 feet to 2.9 feet). The uncertainty reflected in the ranges of these projections arises from two factors: (1) the estimated trajectories of future GHG emissions, and (2) uncertainty in various representations of climate processes, which manifest as the differences among the global climate models that were used to estimate these projections. These differences reflect the imperfect scientific understanding of how the climate system responds to increasing GHG emissions and other disturbances.

For illustrative purposes, the following paragraphs in this section discuss results for two global emission scenarios that were selected from the suite of emission scenarios prepared for the IPCC TAR. The first scenario, known as *A1*, represents a future world of very rapid economic growth, global population that peaks in the middle of this century and declines thereafter, and the rapid introduction of new technologies.

The second scenario, the *B1* scenario, describes a convergent world (where all regions experience the same level of development) with the same population trend as in A1, but with a rapid transition to a service and information economy. This is a "green" scenario, with improved global equity but without additional climate initiatives.

The California Energy Commission (Energy Commission) staff created a third scenario—the "350" scenario. The 350 scenario was designed to maintain ambient carbon dioxide (CO_2) concentrations relatively close to their 1990 levels (which was about 350 parts per million).

To estimate the climatic implications of these scenarios, Energy Commission staff used the MAGICC model developed by Dr. Tom Wigley from the National Center for Atmospheric Research. MAGICC is a reduced form model, which has been calibrated with the results of comprehensive global circulation models (GCMs), and used by the IPCC for the TAR to illustrate the potential global climatic effects of a multitude of potential GHG emission scenarios.

Figure 1 (left graph) shows CO_2 emissions (in gigatons of carbon or Gt C) and the atmospheric CO_2 concentrations associated with the A1, B1, and 350 scenarios.[10] This figure suggests that CO_2 emissions must start to decline immediately if we are to maintain current atmospheric CO_2 concentrations (see the 350 scenario). In addition, the earth needs to become a net CO_2 sink by the end of the century under the 350 scenario.

The right graph in Figure 1 shows the climatic consequences of the three emission scenarios. Average global temperatures and sea level continues to increase in all the scenarios. Under the 350 scenario the warming levels off at the end of this century. The situation for sea level rise is especially alarming, because even under the extremely stringent and unrealistic 350 scenario, the sea level continues to rise, and this increase would continue for centuries, as reported by others.[11, 12] Similar overall conclusions have been reported using the outputs from fully coupled global climate models.[12]

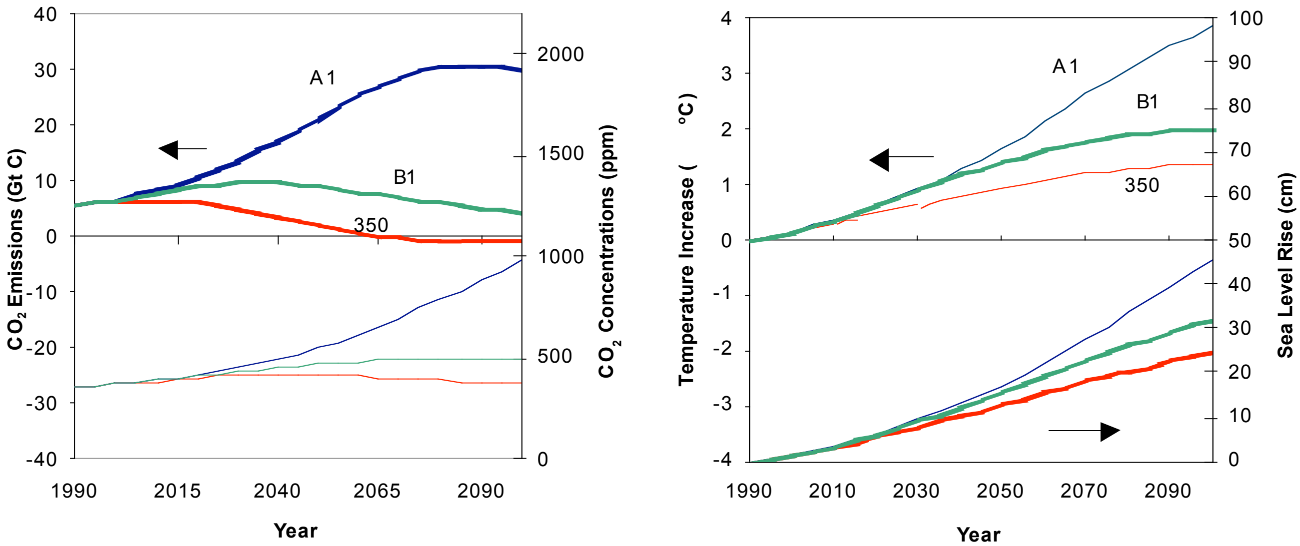


Figure 1. Average Global Temperature and Sea Level Rise Under Three Illustrative Emission Scenarios

It should be clear from the above discussion that our planet will experience some level of warming and sea level rise regardless of the actual emission path that we may follow. This is the result of the accumulation of past emissions in the atmosphere that remain there for decades and the high thermal inertia of the oceans. Emissions must be reduced, however, to decrease the rate of temperature increase and sea level rise, as demonstrated by the divergence of results for the three emission scenarios at the end of this century. At the same time, for the next few decades, the different emission scenarios do not show much variation in outcomes for temperature and especially for sea level rise.[13] Under these circumstances, identification of adaptation measures in the medium and long term should also be a priority.

The IPCC is now in the process of preparing the 2007 Fourth Assessment Report. New global climate model runs have been submitted to the IPCC and are available to the scientific community for analyses and for climate impact and adaptation studies. It is unknown at this time how these modeling runs, which use the modern version of the different climate models, differ from the projections reported in the 2001 IPCC TAR.

Some studies already reported in the peer-reviewed literature, however, suggest that projections of global warming may have been understated and that its impacts may become more severe than previously estimated.[14, 15] The reason for this new viewpoint is due in part to a new approach that is emerging in the technical literature for estimating potential future climate scenarios.

Under this new approach, some key model parameter values are allowed to change, within reasonable bounds, during each simulation. This strategy incorporates uncertainty more completely into the climate projections and supports the notion that climatic changes could be more dramatic than what was reported in the Third Assessment Report.

As indicated previously, the IPCC has estimated global increases in sea level rise that may go from 0.09 to 0.88 meters (0.3 feet to 2.9 feet) by the end of this century. It should be noted, however, that these estimates (which were released in 2001) do not account for mechanisms that could provoke the potential collapse of part of continental ice, such as the Antarctic ice sheet,[16] which could boost substantially the rate of increase and the absolute level of sea level rise.

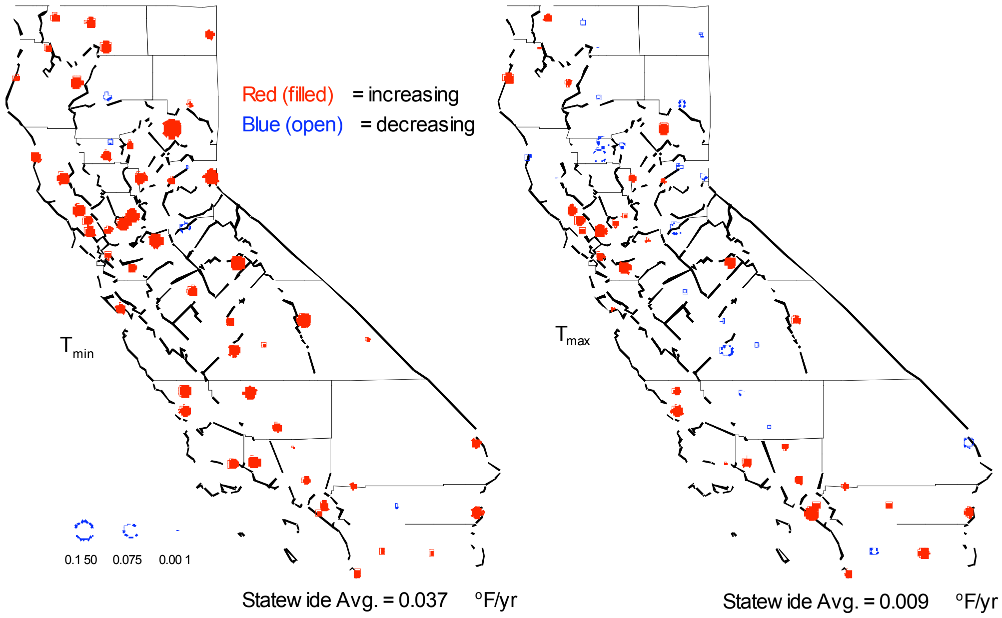
3. Climate Change in California

This section discusses climatic trends in California and presents climate projections for the state.

Climatic Trends in California

California is experiencing a warming trend, similar to other parts of the world.[17, 18] For illustrative purposes, Figure 2 presents average twentieth century summer temperature trends for the stations that are part of the United States Historical Climatology Network, which is maintained by the National Oceanic Atmospheric Administration (NOAA). The trends are based on about 100 years worth of data for each one of the stations in Figure 2. As shown in Figure 2, both maximum (Tmax) and minimum (Tmin) daily average summer temperatures are increasing on a statewide basis, but nighttime (Tmin) warming is more pronounced. The usually reported average temperature trends are mainly driven by the increases in minimum temperatures.[19] Annual average temperatures show similar trends, but nighttime temperature increases are more pronounced in the summer and fall seasons.

Measurements taken in other stations in the United States and in the rest of world demonstrate that stronger nighttime warming is a very common feature.[20] Outputs from GCMs also suggest that this trend may continue in the future,[21] and that a more-rapid increase in Tmin may be a climate change signal.[22]



Data Source: U.S Historical Climatology Netw ork

Figure 2. Maximum and Minimum Daily Average Summer Temperature Trends in California

The veracity of overall warming in winter and spring in western North America, including California, has been reinforced by several studies that report a trend for a greater portion of the annual river runoff to be occurring in the wintertime.[23, 24] The main driver for this trend is believed to be a general atmospheric warming that induces an early onset of snowmelt.

California precipitation trends are not as clear as its temperature trends. Some studies have reported significant increased precipitation levels,[25–27] but there are still some doubts about the actual trend.[23] Differences in trends can arise from the selection of the period used in the analyses, the method used to estimate trends, and the stations selected for the analyses. Some researchers have also suggested that aerosols emitted from urban areas may be severely impacting precipitation level in high elevations in the Sierra Nevada and other locations, further complicating the task of estimating precipitation trends.[28]

Higher temperatures have also affected spring snow accumulation in western North America. For example, some scientists have reported a decline in the amount of snow on April 1, which is an important date for water managers because it is the date that they estimate the amount of water stored in the snow and determine how much water will be available to satisfy water demands in the spring and summer.[29] Many agricultural and urban water planning decisions for the rest of the year are based on these assessments.

Figure 3 shows that the amount of water contained in the accumulated snow on April 1 has been mostly declining in the Western United States,[30] consistent with the observation that snowmelt timing has advanced to earlier in the season.

Snow in high elevations in the southern portion of the Sierra Nevada, however, has been increasing.[23, 24] (Refer to the map on the right in Figure 3 to identify the high elevation regions.) These trends conform to the understanding among researchers and modelers that high-elevation regions tend to be less susceptible to a warming trend (a small warming in the cooler high-elevation areas result in temperatures still below freezing levels).

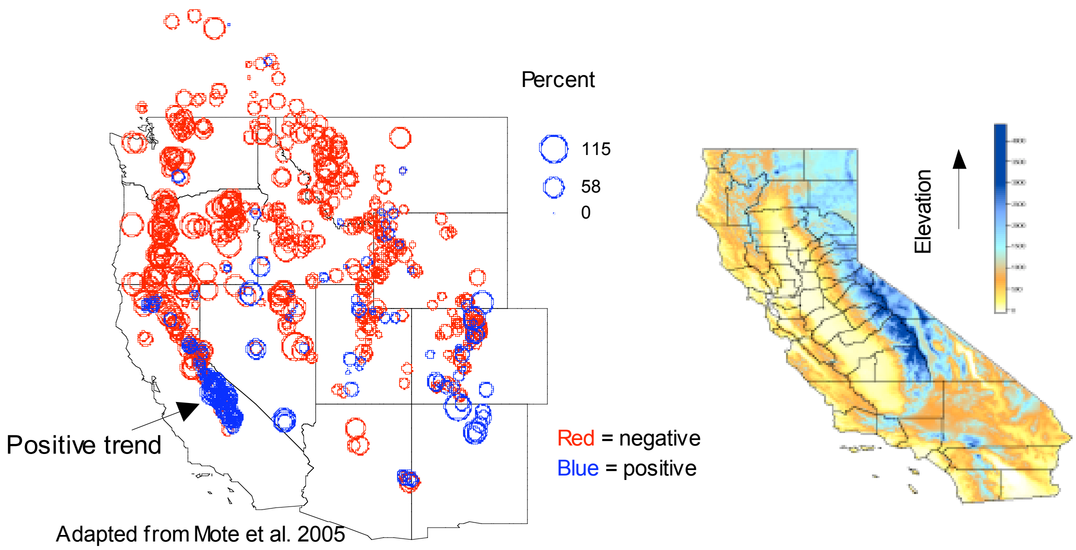


Figure 3. April 1 Snow Level Trends: 1950–1997

Sea level is also increasing in California and in many locations throughout the rest of the world. Figure 4 shows relative sea level height for several stations in California. There is also some evidence that high sea level extremes associated with winter storms have been increasing since about 1950 at the San Francisco tide gage.[31] These gages indicate that sea level is rising in California and most likely will continue to rise with global warming, as the result of thermal expansion of the oceans and melting of ice caps and ice sheets in the polar regions.

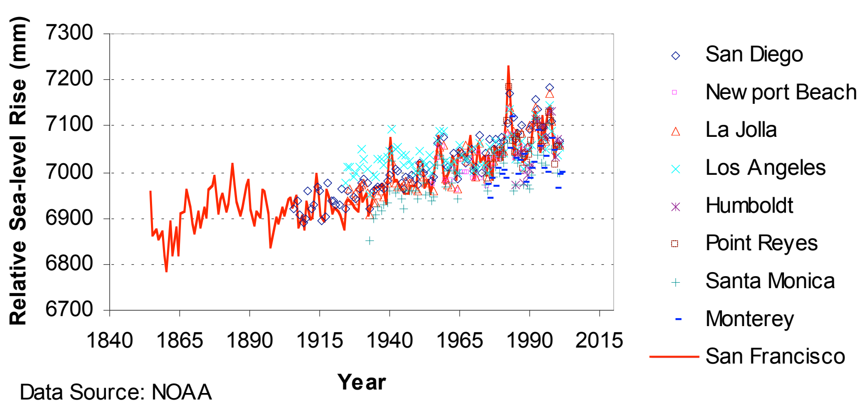


Figure 4. Relative Sea Levels in California

Climate Projections for California

How would California's climate change as the result of an increased concentration of GHGs in Earth's atmosphere? The scientific community has produced a series of preliminary projections trying to address this question;[32–35] however, it is important to emphasize that there is a very high level of uncertainty in any regional projection.

Temperatures are expected to continue to increase in California, but the estimated degree of warming is a function of two factors: (1) the global emission scenario used for the analysis, and (2) the global circulation model selected. Dr. Michael Dettinger from the U.S. Geological Survey and the Scripps Institution of Oceanography (Scripps) has convincingly demonstrated this finding in an influential PIER report and subsequent journal paper,[36, 37] and others have reported similar results for the West Coast.[38]

There seems to be a tendency for steeper increases of temperatures with higher emission levels, especially for the second half of this century.[39] Dr. Dettinger also demonstrated a complete lack of consensus by the different models with respect to California precipitation. A few models yield substantial increases in precipitation levels from historical conditions, while others show slight decreases.

As indicated previously, new climate projections, using global circulation models, are now available from the IPCC for the Fourth Assessment Report. The Energy Commission staff has accessed these modeling results and performed some preliminary analyses using the outputs of twelve global circulation models and two emission scenarios (A2 and B1). The preliminary conclusion is that the overall findings reported by Dr. Dettinger would not change, but more models are suggesting a drying trend.

Some models simulate large increases in precipitation patterns for California, while others suggest small decreases in precipitation levels (see Figure 5). For the low-emissions scenario (B1) (not shown in Figure 5), however, increases in precipitation levels do not seem to be as dramatic as the ones simulated for the high-emissions scenario (A2).[40]

Figure 5 shows the projected changes in precipitation levels generated under the A2 emission scenario for four representative global circulation models. The ISPL and CSIRO climate models suggest that precipitation levels would increase in Northern California, while the Hadley3 and PCM models project no overall changes from historical (1970–2000) levels.

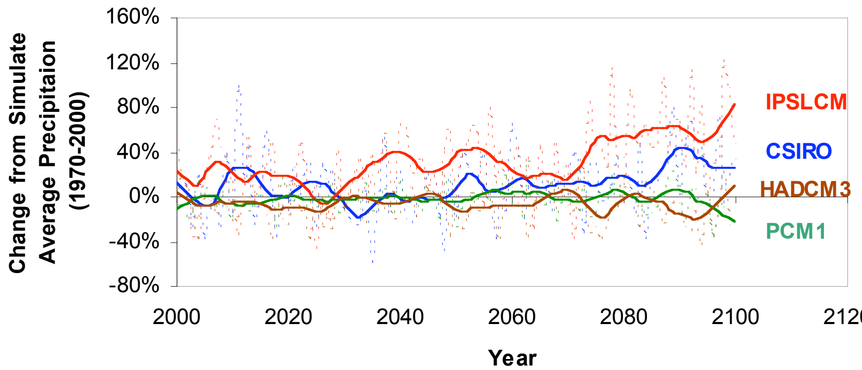
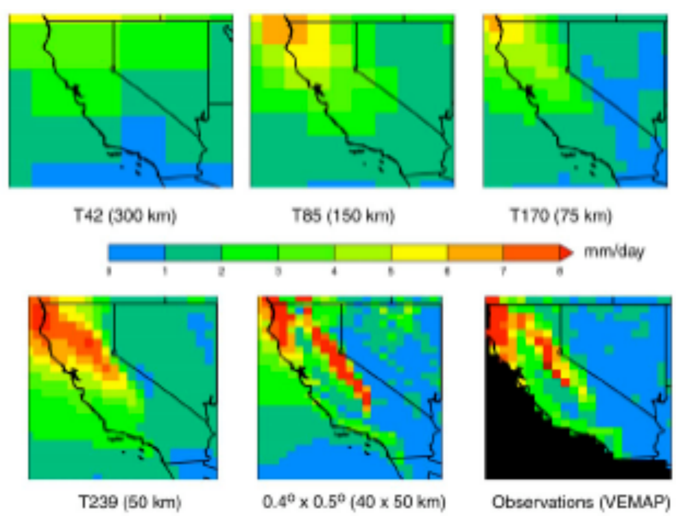


Figure 5. Precipitation Projections for Northern California: IPCC Emission Scenario A2

Thus far, this presentation has focused on trends suggested by the outputs from coupled ocean-atmosphere GCMs for California. These models, which typically have a horizontal resolution of about 200 to 300 kilometers (km), do not provide enough geographical resolution for in-depth regional impact and adaptation studies. Figure 6 presents the simulations of annual mean precipitation in California performed with an atmospheric climate model at different spatial resolutions. Also shown (bottom right) is observed precipitation on a 0.5 degree (latitude/longitude) grid. As spatial resolution is refined, simulated precipitation more closely resembles observed. The lower center panel shows results obtained using a new approach for calculating the atmospheric circulation, which allows topography to be represented more accurately.[41] This figure shows the importance of high-level geographical resolutions to obtain realistic simulations of climatic conditions at the regional level.



PIER Report by Dr. Tom Wigley, 2004. Graph generated by Dr. Phil Duffy at LLNL.

Figure 6. Level of Geographical Resolution by Current Global and Regional Numerical Models

How would changes in temperature and precipitation levels affect snow conditions in California? Scientists at Scripps suggest dramatic changes. For example, they estimate that spring (April 1) snow water equivalent in the California snow pack would decrease on the order of 50 percent by 2090 under a regime in which precipitation was the same or slightly lower as historical observations, but with warmer temperatures given by a “business-as-usual” climate scenario based on the results of the Parallel Climate Model (PCM).[42]

In agreement with the historical trend shown in Figure 3, the modeling result reported by scientists at Scripps suggests that spring snow losses in the high-elevation regions of the southern Sierra Nevada would not be as severe as those in the lower-elevation northern Sierra Nevada.

Figure 7 presents the results of a study conducted by Miller et al.[43] and Lund et al.[44] for the Central Valley, which historically represents about 72 percent of all the inflows to the state’s intertied water system. Note that Figure 7 only presents the results of two of the scenarios analyzed by Miller and Lund. The interested reader should consult their reports for further results and details about their regional climate and hydrological modeling work.

Figure 7 illustrates the runoff from the mountains into the modeling domain of the CALVIN model[45]—an economic-engineering optimization model of the entire intertied California water system, for which these hydrological projections were developed. The runoff in this figure represents the natural or unimpaired flows, as if there were no dams and other man-made facilities storing or diverting water. The two global models represent two relatively extreme scenarios, with the Hadley model (version 2, or Hadley2) producing extremely high precipitation levels, and the PCM projecting a modest reduction of precipitation levels from historical conditions for California.[46]

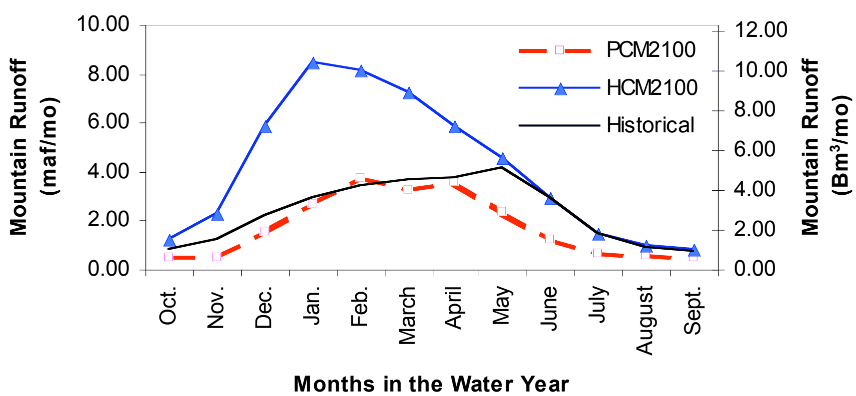


Figure 7. Natural Runoff to the CALVIN Modeling Domain: Average Conditions from 2070 to 2100

As shown in Figure 7, a warmer climate would affect the timing of runoff, in agreement with the historical record. This trend would result from an earlier snowmelt, in combination with the potential for a higher fraction of the precipitation to fall as rain instead of as snow. The warmer winters would also produce a higher frequency of floods as the area of Sierra watersheds that are receiving rain instead of snow increases.[33, 47]

Some researchers have attempted to quantify potential runoff trends, using various metrics. One of the most useful metrics is center of mass (CM), the date when 50 percent of the discharge weighted stream flow season has occurred in a given year. A recent paper analyzing a multitude of climate projections for California suggests that 50 to 70 years from now, CM would advance by about 11 days in the northern portion of the Sacramento-San Joaquin region and by about 18 days in the southern portion of this region, on average. [48]

The same study suggests that thirty years from now, CM would advance by about one week, on average.[49] Others have estimated a 30-day shift in CM for the PCM model by the end of this century.[50] The consensus among climate change researchers indicates that climate change will shift the runoff in traditional snowmelt basins to heavier winter flows and lighter spring and summer flows.

4. Potential Climate Change Impacts in California

A modified climate will affect virtually every aspect of California's economy and natural resources—with energy supply and demand, water resources, agriculture, vegetation patterns, ecosystems, air quality, public health, and sea level rise among them. This section briefly summarizes the potential impacts to key sectors based on the results of recently completed reports for the Energy Commission's PIER Program and scientific papers published in the peer-reviewed literature. This summary only highlights some of the major scientific findings.

It is important to underscore that the exploratory studies described in this section were somewhat time- and resource-limited. However, they provide useful insights and indicate that human adaptation will be costly, that natural systems are extremely vulnerable, and that a holistic view of the potential impacts (including other stressors) should be attempted.

Energy Supply

Climate change may affect the amount of electricity produced in hydroelectric power plants, which contributes about 20 percent of the electricity generated by

California's in-state power plants. California also imports significant amounts of hydropower from the Pacific Northwest.

California has a vast infrastructure of reservoirs and dams with multiple purposes such as flood protection, water supply to urban areas and for agricultural use, recreational activities, and electricity generation. In general, electricity production is not the main purpose of these facilities. These reservoirs can accumulate a considerable volume of water. For example, the storage capacity in the major reservoirs on the Sacramento/San Joaquin watershed is about 35 cubic kilometers, which roughly equals the average annual freshwater endowment for this major watershed.

As indicated above, warmer temperatures will affect the snowpack on which the state depends for a reliable, year-round water supply. Changes in precipitation levels and patterns and timing of snowmelt would alter the amount of electricity that hydroelectric facilities could generate. It would also affect seasonal availability, with less water available for hydroelectric generation in the spring and summer months, when demand is the highest. In addition, there is a high likelihood that changes in precipitation and runoff patterns would lead to changes in broader water policies and end-use priorities, which could place further limitations on hydroelectric production.

Pacific Gas and Electric (PG&E) produces about one-third to one-fourth of the in-state hydroelectric generation in California. PG&E's hydropower generation, on average, originates from the following runoff sources: groundwater aquifers (38 percent); snowmelt (36 percent); and rainfall (25 percent).[51] According to PG&E, "a recent review of PG&E's water and climate data indicates that a change in runoff timing has taken place with a decrease in snowmelt-produced runoff during the past 50 years as compared with the first half of the twentieth century. This change appears to be continuing in a trend-like manner toward decreasing runoff from snowmelt."[52]

Increased temperatures as the result of climate change will affect relatively low-elevation watersheds most drastically. This is the situation for most northern PG&E hydroelectric systems, the Pit-McCloud, and the North Fork Feather River projects that represent about 55 percent of PG&E's annual hydroelectric generation.

Pacific Gas and Electric's Pit-McCloud system is located in an area with very porous ground of volcanic origin, which facilitates rapid aquifer recharge. A substantial portion of this system's annual flow is attributed to aquifer outflow from at least the prior year's precipitation. The timing of precipitation or snow melting is not the primary factor affecting the recharge of these aquifers. For this reason, it is believed that hydropower generation from this system would not be as affected by shifting of precipitation patterns[52] as it would by general reductions in precipitation levels.

About 90 percent of the North Feather River watershed lies at or below 1800 meters (5900 feet) above sea level and is, therefore, vulnerable to an upward shift of the line demarking freezing conditions. This system has much less porous volcanic drainage than the Pit-McCloud system, so a shift of runoff to the winter season should result in decreased generation, because much of the winter runoff cannot be captured and must be spilled to maintain storage reservoir capacity as required for flood control—one of the main objectives of these reservoirs. In addition, during high winter water flows, the hydroelectric facilities may need to shut down to avoid damages to the system.[52]

The PG&E hydropower generating units that receive runoff originating from the high-elevation regions in the southern portion of the Sierra Nevada may not be as susceptible to climate change as the units located in relatively low-elevation watersheds for the reason discussed before. This is in agreement with the April 1 snow level trend shown in Figure 3.

Two studies reporting hydropower generation in the state under different climate scenarios have been published in the last few years. The first, a study conducted by researchers from the University of California at Davis (UC Davis), concluded that if precipitation increases significantly, there would be substantial concomitant increases in the annual amount of electricity generated in hydroelectric power plants in the state.[44]

On the other hand, if precipitation remains the same or decreases slightly, there would be substantial reductions in the amount of electricity generated from this low-cost energy source—and again, the decreases would be more pronounced during the summer. This scenario would translate into reductions of about 30 percent in annual electricity generation by the end of this century.[44]

The second study produced by researchers associated with the University of Washington in Seattle estimates a loss of hydropower generation of about 10 percent per year by the end of this century for a relatively dry scenario.[53]

Both studies represent important advances to our quantitative understanding of the potential implication of climate change on hydroelectric generation, but additional studies are warranted.

It is important to emphasize that even relatively small changes in in-state hydropower generation result in substantial extra expenditures for energy generation, because this “free” generation must be purchased from other sources. For example, a 10 percent decrease from the current average in-state generation level of this renewable energy source (assuming a price of about 10 cents per kilowatt-hour) would result in an additional $3.5 billion per year in net expenditures to purchase enough electricity to replace the electricity that otherwise would be generated using hydroelectric resources.

With the increasing demand for electricity in California and on the West Coast, the relative contribution of hydropower to total generation will diminish with time, even in the absence of climate change. In the distant future, California may not be able to count on large transfers of hydropower from the Pacific Northwest, given the expected increase in local demand in this region and, perhaps, decreased ability to generate electricity in the summer months in the Pacific Northwest. Studies addressing this topic have not been reported yet in the technical literature.

Energy Demand

Climate change is also likely to affect energy demand in California. A paper published in 1992 reports results from one of the earlier studies designed to estimate the impacts of climate change on electricity demand. [54] The authors used the energy forecast models that were developed for or by the Energy Commission to estimate electricity demand from a variety of planning areas (for example, PG&E and Southern California Edison).

The authors estimated demand for residential units, commercial buildings, and water pumping for urban and agricultural use. They assumed that climate change would substantially reduce the amount of surface water available for irrigation, similar to the situation that existed during the 1976–1977 drought. The study included a scenario with more warming at night than during the day.

Under the worst-case scenario (a 1.9ºC increase), electricity requirements in 2010 increased by about 7,500 gigawatt-hours (GWh) and required an additional peak capacity of 2,400 megawatts (MW). This trend would represent an increase of about 2.6 and 3.7 percent in energy and peak generation capacity, respectively, from the 2010 base case. More warming at night lessened the electricity demand, but the decrease was not dramatic.

A more recent study estimated that by 2020, increases in net energy expenditures for natural gas and electricity in the residential and commercial sectors could be relatively small in a mild warming scenario, or they could be in the order of $2 billion, in an extreme case.[55] The increase in net energy expenditure results from an increase in summer cooling demand that overrides the decreases in heating demand from warmer winter temperatures. In relative terms, $2 billion dollars represent about 6 percent of California's current expenditures in energy (natural gas and electricity) for cooling and heating in the residential and commercial sectors,[56] and it would represent an even smaller fraction by 2020.

As demonstrated by Baxter and Calandri,[54] climate change adds an additional level of uncertainty for energy demand forecasts, but other factors such as population and economic growth seem to have more impact on final energy demand. However, it should be clear that potential climate change impacts on energy demand are not trivial.

Water Resources and Agriculture

California's engineered water systems are already overtaxed, and every major water supply source in California is beyond its physical or legal capacity to be sustained.[57] Currently, more than half of the state's population depends on water imported from outside their area.

A recent PIER report by Lund et al. (2003)[44] suggests that California's water system would be able, at a significant cost, to adapt to these new climatic conditions. Drastic changes in management practices would need to be implemented in order to allow the transfer of water to sectors where it is the most economically beneficial. In general, this change means substantial transfers of water from agriculture to urban areas.[44] It is unclear how this rational water use could be achieved, given the historical animosity surrounding water management in California. However, a drastically changing climate may be the catalyst that induces these changes.

As hydrographs shift to earlier in the year, the risk of flooding will also substantially increase, especially for the wet scenarios. In fact, under the Hadley2 scenario presented in Figure 7, the existing infrastructure of dams and reservoirs would most likely not be able to avoid catastrophic flood events.[44]

For the agricultural sector, a recent study suggests that farmers may switch to high-value, low-water-consumption crops—which would reduce somewhat the economic losses for this sector if precipitation levels in the future are less than the current levels.[58] However, this overall statewide result masks the drastic potential for negative economic effects in certain California regions, such as the Sacramento Valley.

The potential for a reduction of water consumption in the agricultural sector seems to be substantial. Four crops (alfalfa, irrigated pasture, cotton, and rice) represent less than 10 percent of total value of crops produced in the state—yet their production consumes from one-third to one-half of the water used by the agricultural sector.[59]

Others have reported potential significant impacts in the dairy and wine industries in California.[39] A recent preliminary econometric study of temperature impacts on the state's agricultural productivity supports the finding of overall negative impacts in that sector.[60]

Vegetation Patterns and Ecosystems

California has a highly diverse landscape that ranges from cool, wet redwood forests in Northern California to hot, dry Mojave and Colorado deserts in Southern California, with many variations in between. As a result, the state hosts more plant and animal species than any other state, including 300 natural plant and animal communities and 178 major habitat types.[61] Several studies are already reporting significant impacts on species or in ecosystems in California and suggest that these changes are most likely attributed to a warming atmosphere.[24, 62–71]

Changes in vegetation patterns will be one of the main drivers affecting ecosystems. Lenihan et al. (2003)[72] used a state-of-the-art/science dynamic vegetation model at the highest geographical resolution ever attempted for studies in California (10 km by 10 km). Their modeling results suggest significant changes in vegetation patterns in California, but the results are dependent on the climate scenario used for the analysis.

Wet scenarios result in the expansion of forest in northern California and grassland in southern California. If California gets drier, grasslands will expand. For both scenarios, alpine and sub-alpine ecosystems would be reduced substantially as vegetation that is currently in lower elevations moves uphill. The dynamic vegetation model suggests that the frequency and the size of fires would increase under most climatic scenarios, with such an increase becoming significant only in the latter part of this century.

The drier scenarios resulted in more frequent fires and more area consumed by fires; whereas, the wetter scenarios resulted in fires of greater intensity, because more biomass grows under wet conditions. Accumulation of this biomass would add increased fuel (vegetation), which would be consumed by fire during occasional dry periods.

Two other studies have examined the potential impact of climate change and forest fires in California. Torn, Fried, and Mills (2004) used a model that explicitly takes into account human responses to fires to simulate initial forest fire control efforts, area burned in contained fires, and the number of fires that grow too large for containment after initial attempts to control them.[73] The researchers assumed current conditions for all the other factors affecting fire. For example, they assumed the current vegetation patterns for the future scenarios. Their main conclusion is that the number of escaped fires would increase by 50 percent in the South San Francisco Bay area, 120 percent in the Sierra Nevada, and remain unchanged on the north coast.

Researchers associated with the Desert Research Institute and Scripps conducted the second study. They reported an increase of fire danger for the northern Rockies, Great Basin, and the Southwest under a “dry” scenario. The researchers used a parameter that depends on daily maximum and minimum temperatures and relative humidity; temperature and relative humidity at the local 13:00 time; and precipitation amount and duration for the previous 24 hours.

The number of days with the value of this parameter that has been historically associated with the largest fires (≥ 400 hectares) seems to increase in California by about 4 days from a statewide average modeled number of about 40 days for the 1975–1996 control period.[74] This study assumes that meteorological conditions are the main driver for large fires. It did not attempt to consider potential changes of vegetation patterns as the result of climate change.

Forces such as land-use changes, invasive species, and air and water quality degradation already threaten California's rich abundance of flora and fauna. Climate change will be another stressor that may amplify the effect of these forces. As part of an overall study on climate change prepared for the Energy Commission,[75] researchers from the University of California, Berkeley (UC Berkeley) extrapolated current urban development patterns to the end of this century. They used two population growth scenarios with the high scenario representing a population growth to 92 million inhabitants by 2100.

Figure 8 presents the modeled distribution of urban areas under current conditions and under the 92-million-inhabitant scenario. This study suggests that an increase in population and a continuation of historical urbanization trends would drastically increase the urban footprint in the state. For example, the area close to Highway 99 from Sacramento to Bakersfield may become completely urbanized by the end of this century. Some argue that this level of urbanization will not materialize, because they find it difficult to imagine, and assume that the state will eventually move away from current urbanization patterns.

Smith and Galbraith (2003)[76] used the Lenihan et al. (2003)[72] estimated changes in vegetation patterns described earlier in this section, together with the UC Berkeley urban projections, to study the impacts of climate change and urbanization on coastal sage scrub, which is an important ecosystem in California and home to about 100 endangered or threatened species in Southern California.

The main finding from the Smith and Galbraith[76] study is that both urbanization and climate change would severely reduce the area for this particular ecosystem. The study is indicative of the types of outcomes that may be expected in other key California ecosystems, and suggests potential, serious implications for the health of the state's ecosystems.

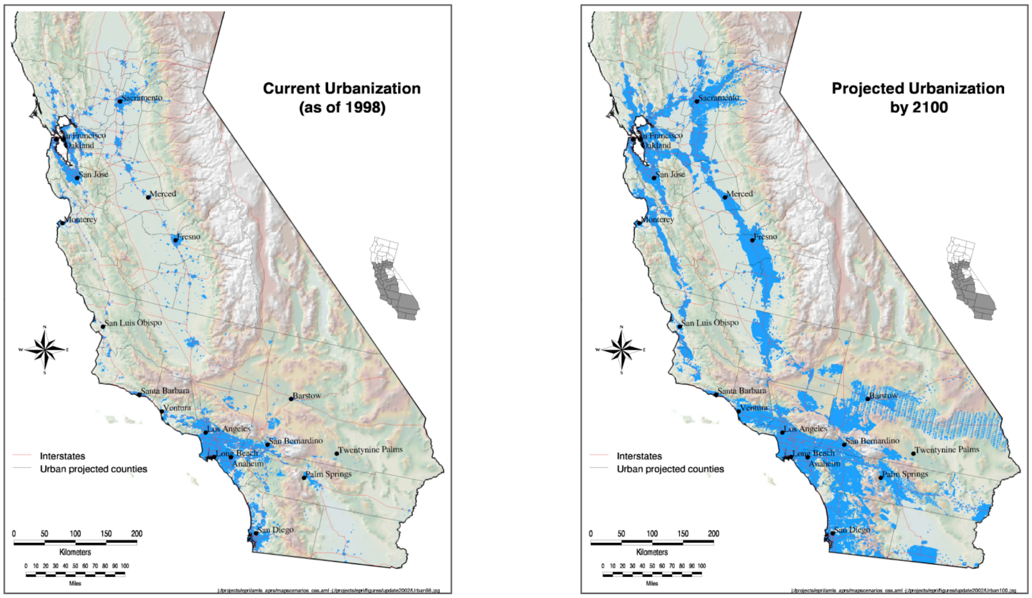


Figure 8. Current and Projected Urbanization Patterns in California

Air Quality and Public Health

The observed trend towards higher surface temperatures in California may complicate efforts under way to improve the state's air quality conditions. However, as indicated previously, the trend is not necessarily a uniform increase in temperatures in the diurnal cycle. Minimum temperatures are increasing at a faster rate than maximum daily temperatures, and this trend may continue.[21, 77]

Meteorology and emissions control ground-level ozone concentrations. Have the observed changes in meteorology affected ozone concentrations in California? A very preliminary study conducted by scientists associated with the South Coast Air Quality Management District (SCAQMD) tentatively suggests that this may be the case.

Figure 9 shows the average of daily measured maximum ozone concentrations in the Los Angeles air basin (left graph). Ozone levels depend both on emissions of oxides of nitrogen and reactive organic compounds and meteorological conditions. If long-term average weather conditions (i.e., climate) do not change and if emissions remain constant, ozone trends should remain flat. Using different statistical techniques, scientists can differentiate changes in ozone that are attributable to meteorology from those that are attributable to emissions. Using these mathematical relationships, one can estimate the changes in ozone levels that would have occurred if emissions would have remained constant year after year (e.g., at the 1981 levels).

The right graph in Figure 9 shows an estimate of what concentrations in the Los Angeles air basin would have been if emissions would have remained constant at the 1981 levels for the period shown in this figure. The small positive slope of the trend line in the graph on the right in Figure 9 tentatively suggests that changes in meteorological conditions have reduced the effectiveness of the emission control programs adopted by this air district. Further studies should be conducted on this very important subject.

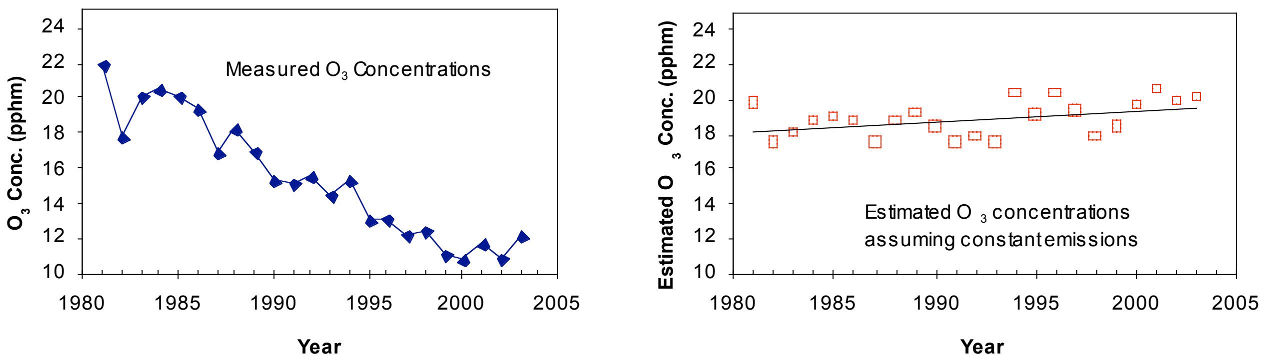


Figure 9. Average Daily Maximum Ozone Concentrations SCAQMD (parts per hundred million)

Changes in precipitation patterns or drier conditions may also affect particulate matter (PM) levels in the San Joaquin Valley. There is a fairly good association between PM levels and the amount of rain falling in the Valley, as shown in Figure 10. Drier conditions reduce the overall air cleansing effect of rain, because even small amounts of precipitation clean the atmosphere from particular matter, at least for the sizes of concern to air quality regulators—$PM_{2.5}$ and PM_{10} (particles smaller than 2.5 and 10 microns in diameter, respectively).

Historical relationships between ozone levels and temperature should not be used to estimate the potential effect of climate change on ozone concentrations. Ozone is both a function of temperature and solar radiation, and the last two quantities are highly correlated. Other potential meteorological changes from climate change, such as temperatures aloft and wind fields, may also affect how climate change could impact ground-level ozone production.

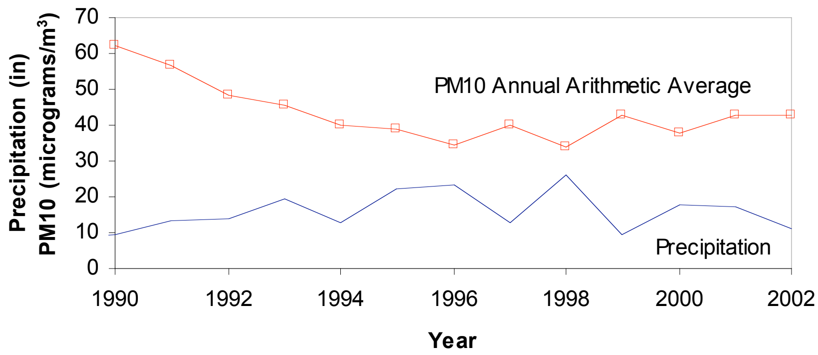


Figure 10. Annual Average Precipitation and Particular Matter (PM_{10}) Concentrations (San Joaquin, Stanislaus, Merced, and Fresno Counties)

A recent modeling study has examined the potential effect of climate variability on efforts designed to achieve the ozone and PM standards in the Los Angeles region. The results of that study suggest that higher temperatures would make it more difficult for air districts to comply with the ozone standards, but would somewhat reduce ambient PM concentrations.[78] Ammonium nitrate dominates PM concentrations during the worst wintertime PM events in California, and higher temperatures shift ammonium nitrate (which is a solid) to its gaseous precursors, which reduces PM concentrations.

Higher temperatures may also affect human mortality and morbidity. Heat waves throughout the state would increase in frequency and intensity, and, for example, human mortality associated with high temperatures in the Los Angeles region could increase from about 160 deaths per year to about seven times that amount.[39] However, more studies are needed to better understand the potential effects of climate change on public health in California.

For example, researchers conducting the above study did not consider the potential confounding effect of air pollution when they developed the statistical associations between high temperatures and mortality, even though several studies have found an association between ozone and PM and human mortality. In addition, some researchers project increased coastal upwelling in central and northern California in the summer season, reducing (or at least mitigating) projected increases in temperatures in the state's northern and central coastal cities, and potentially reducing the reported health effects described above.[79, 80] Some studies have suggested that increased coastal upwelling is already occurring, as expected from an increased temperature differential between the ocean and inland areas.[81]

Effects of Sea Level Rise

Neumann et al. (2003) estimated the optimal cost of coastal protection under different sea level scenarios in California.[82] Because of the high cost of real estate in the state, this study found that coastal protection with sea walls, beach nourishment, and other measures is always cost effective. The costs to protect low-lying areas can be as much as $100 million per year on a statewide basis, assuming a sea level rise of about 1 meter by the end of this century. The study did not estimate impacts on wetlands and other ecosystems and did not consider the potential environmental impacts of coastal protection, which could be significant.[83]

The Sacramento-San Joaquin Delta is the region of the state from which fresh water is transferred from Northern to Southern California. It provides about two-thirds of the water consumed by Californians. Originally the Delta was a tidal freshwater marsh with a network of channels, sloughs, and islands. Beginning in the late 1800s, human intervention has resulted in the loss of enormous amounts of carbon-rich soils as the result of burning and farming.[84]

Agricultural tillage exposes the carbon in the soil, resulting in its oxidation and release to the atmosphere as carbon dioxide.[85, 86] For this reason, the Delta now includes a series of islands that are below mean sea level in some places by more than 8 meters (26 feet). A network of about 1700 kilometers (1056 miles) of levees protects the islands for the water. Serious disruptions to the Delta can dramatically affect water availability to Southern California.

Subsidence, due to the loss of carbon-rich soil, will continue in the Delta under current practices. This factor and sea level rise will increase the relative height of the water with respect to ground level inside the islands. A rise in sea level increases the pressure that the water exerts over the levees, increasing the probability of levee failure.

A path-breaking study by Jeffrey Mount and Robert Twiss[85] published in 2005, estimates the potential impact of subsidence and a moderate average increase of sea level rise of about 2.5 mm (0.1 in.) per year (a total of 25 centimeters (9.8 in.) from 2000 to the end of this century). Mount and Twiss developed an index that (on a broad scale) measures the relative risk of island flooding. This index, identified as *Levee Force Index* (LFI), goes from 100 units in year 2000 to about 150 units in 2050 (see Figure 6 in Mount and Twiss), indicating a 50 percent increase in the hydrostatic forces exerted on the levees, substantially increasing the likelihood of costly levee failures. Because these forces are a quadratic function of the elevation difference between the water in the channels and the average elevation inside the islands, more rapid increases in sea level rise would substantially increase these hydrostatic pressures and further increase the likelihood of levee failures.

According to Mount and Twiss, the program that is designed to support maintenance and levee upgrades is not adequate to protect against 100-year flood events. If this is the case, and since the probability of a 100-year flood event in any given year is 0.01, the probability that such a 100-year flood will occur in the next 50 years is 0.40.[87] This represents a two-in-five chance of one of these events occurring in the next 50 years. Climate change will acerbate this potential problem if there is an increase in flooding events, as suggested under some climate projections for California.

5. Potential Adaptation Measures to Climate Change for California

As discussed previously, due to the long atmospheric lifetime of GHGs (for example, about 100 years for carbon dioxide) and the high thermal inertia of the oceans, our planet will continue to experience some level of warming and sea level rise. For this reason, it is prudent to identify options to adapt to climate change, in order to reduce negative impacts and enhance any potential positive impacts that may result from it.

Dr. Robert Wilkinson from the University of California at Santa Barbara has identified a series of “no regrets” adaptation strategies, such as: (1) increased water use efficiency; (2) limiting the footprint of development on the landscape, particularly in vulnerable habitats such as wetlands and areas subject to fires, floods, and landslides; (3) creating nature reserves designed to accommodate future climate changes and necessary range shifts and migrations of plants and animals; (4) reducing urban heat island impacts; and (5) using permeable pavements so that storm water runoff can be beneficially used to recharge groundwater systems.[88]

What is needed now is a quantification of these and other adaptation measures to estimate how much these no regrets strategies can alleviate potential negative climate change impacts. The reader is encouraged to read his report for a more comprehensive list and description of these measures.

The Energy Commission’s PIER Program has started in-depth adaptation studies, including: (1) development and exploration of probabilistic California climate projections for impact and adaptation studies; (2) development of higher resolution regional model tools to explore effects of climate change and land use change; (3) creation of a dynamic ecological model to be used for the development of biodiversity conservation strategies; (4) demonstration of probabilistic seasonal forecasts, to improve the management of water reservoirs in the state; (5) installation of climate reference stations to track and, if possible, detect climatic changes in the state; (6) development of a process-based shoreline model to estimate how our coastal area may change in the future with sea level rise; and (7) enhancements to the CALVIN water system model, to investigate potential adaptation measures under a wide variety of scenarios. The following section presents more information about these and other research projects.

6. State-Sponsored Climate Change Research in California

Although several state agencies support climate change research at some level, the California Air Resources Board (CARB) and the Energy Commission are the most active.

The California Air Resources Board is funding studies to characterize black carbon and organic carbon releases, investigating emission levels from cars and trucks, improving emission inventory methods for both CO_2 and non-CO_2 gases, and evaluating the potential public health effects of climate change. It is also sponsoring research to determine the climate change benefits of air pollution control activities.

The Energy Commission's PIER Program has developed a long-term strategic research plan designed to complement national and international research efforts, in order to produce policy-relevant research products.[89] The PIER research activities are heavily coordinated with other state and federal agencies.

To implement this research plan, the Energy Commission has created the California Climate Change Center (the Center). This virtual research center has four research branches: (1) a branch led by the Scripps Institution of Oceanography at the University of California, San Diego that conducts work on climate monitoring, analysis, and modeling; (2) a branch led by the University of California, Berkeley that studies the economic response to climate change, including impact and adaptation analyses; (3) a carbon sequestration branch that focuses on research to develop potential carbon sequestration measures and techniques in geological formations and in terrestrial habitats; and (4) a branch that offers competitive solicitations on global climate change research activities that are not currently being conducted (nor planned to be conducted) under the other three branches.

As described in the Energy Commission's climate change research plan, the Center is engaged in an initial five-year research effort, with a first phase of this five-year effort designed to develop the tools and data necessary for in-depth policy relevant analyses. This effort is complemented with a series of related projects designed to produce probabilistic climate projections for California, for both research and state planning efforts.

Both efforts will merge when the tools and models are used with the probability scenarios for impact and adaptation analyses. Finally, the Center will produce a "California Assessment Report" at the end of the five-year initial research period that will strive to involve scientists representing the full spectrum of the California scientific community in academia, national laboratories, governmental agencies, and the private sector to produce a compilation of what is known about climate change and relevant to California. Preliminary assessment reports or progress reports will be available before the release of the Center's first assessment report. The first one of these progress reports will be released early in 2006.

The Center's goal is to address the following overarching questions to inform the policy debate in California:

- How will climate change in California in this century?
- How may climate change and population growth affect California's future water resources, including hydropower production and ecological systems?
- What are the potential changes in vegetation patterns in California, and how would they affect and be affected by the state's climate and the hydrological cycle?
- What are the options available to the state to reduce net greenhouse gas emissions and what are their associated costs or benefits?
- What are the costs associated with reducing GHG emissions in other sectors of the economy, in comparison to those of reducing GHG emissions from the electricity sector?
- What emission estimation methods should be improved to better characterize GHG emissions and GHG emission reduction opportunities?
- How would the impacts of climate change and measures to abate GHGs affect California's economy in the coming decades?

The following sections briefly describe some of the overall areas of work being supported by the Commission through the PIER Program. For access to the 30 research reports already available, the reader is encouraged to visit the Web page at www.climatechange.ca.gov/documents/pier_gcc_reports.html. The Center produces about one report per month.

Climate Measurement, Analysis, and Modeling

Scripps has been very active in monitoring climate in remote locations for several years, including the monitoring of sea conditions in the open ocean. The PIER Program has considerably enhanced Scripps' work regarding the monitoring of meteorological and hydrological conditions in California.

For example, PIER has funded the development of a new, low-cost remote monitoring environmental sensing system that has a small footprint. Where conditions are suitable, it can broadcast data on a near-real-time basis. The small footprint is necessary if one is to install these instruments in national parks and other wilderness areas where minimum disturbance of natural conditions is essential.

Scripps and its partners have installed this system in several key locations in Yosemite National Park and the Santa Margarita Reserve. In several of these locations, the data is being transferred using wireless communications to Scripps on a near-real-time basis. Researchers are developing plans to extend the monitoring coverage to other key areas of the state that are important for climate change detection and regional modeling development and evaluation.

For example, transects going from the valley floor in the Sacramento or San Joaquin Valley across the Sierra would be an important long-term contribution to the investigation of the hypothesis that high elevations will warm faster than low elevations, with the subsequent detrimental effects on the snowpack. Scripps is working very closely with other state agencies—especially the California Department of Water Resources, given their existing presence and expertise in this area.

For climate analysis, Scripps has been performing different retrospective studies to better understand how climate is evolving in California. For example, Scripps has been studying how storminess in coastal areas has changed in the state over the last 100 years, to determine if the reported increase in storm activities in the coast since the 1950s is unique in the historical record or is due (at least in part) to normal climate variability.

An extremely important part of this work is the creation of the California Data Climate Archive, which is being hosted by the Western Regional Climate Center in Reno, Nevada. This resource is intended to be an easy-to-access archive of climatic data for California that is available to researchers, governmental agencies, and utilities. The California Data Climate Archive will eventually contain data going back 100 years or more, and it will be the focal point for studies on climatic trend analyses for the state.

With respect to climate modeling, the Center is proceeding methodically, first modeling past conditions before moving into climate projections. Researchers at Scripps are conducting a reanalysis of the historical climate of California in the last 50 years, using the Regional Spectral Model (RSM) at a geographical resolution of 10 km, which may be the highest-resolution reanalysis ever attempted for regional climate studies.

Ongoing work with other research institutions also funded by PIER includes a set of fine scale model simulations to explore how land-use changes that are produced by urbanization and the massive use of irrigation water affects climate in the region. This work is important to better understand reasons for variations in the spatial pattern of warming and for the asymmetric increase in the diurnal temperature profile observed in California. Urbanization and irrigation may have contributed to the faster increase of nighttime temperatures. Scripps is also developing new statistical techniques that could use the outputs of global or regional circulation models directly, to estimate regional climate on a finer scale.

The Center has also launched a regional climate detection and attribution study with scientists at three organizations: Professor Phil Duffy of the University of California, Merced; Dr. Ben Santer of Lawrence Livermore National Laboratory (LLNL); and Dr. Tom Wigley of the National Center of Atmospheric Research (NCAR). The goal of this project is to rigorously determine if a climate change signal is already discernible in California, and if so, to determine how this information could be used to better estimate future potential changes in climate for our state.

With professors Mark Jacobson from Stanford University and Daniel Rosenfeld from Hebrew University of Jerusalem, the Center is investigating the role of aerosols on regional climate and precipitation levels in high elevations. Some preliminary studies by both researchers suggest that aerosols are reducing the amount of solar radiation reaching ground level and reducing precipitation levels in high elevations. The Center is attempting to better understand the role of aerosols to take them into account in future regional climate change studies.

Finally, the Center will start a series of projects designed to produce probabilistic climate projections for California. This includes a project designed to compare regional climate models against observations to identify and address any major problems with the models before they are used to develop climate scenarios.

A related project with Dr. Tom Wigley (NCAR) and UC Santa Cruz will analyze how well global circulation models simulate the transfer of moisture from the Pacific Ocean to the California region. It is possible that models that estimate significant increases in precipitation levels in the state may be incorrectly simulating this important phenomenon.

All of this new knowledge, together with a methodology being developed by Drs. Dettinger and Cayan from Scripps designed to objectively assign probabilities to climate projections, will be used to develop probabilistic climate projections for California.

Development of New Tools and Data Sets

The Center is developing several new tools and models and compiling new data sets for future climate impact and adaptation analyses. This section briefly describes some of these tools and models.

Researchers at UC Davis are enhancing the CALVIN model to be able to perform studies on how the water system may need to evolve with time under different climate scenarios. In addition, the researchers are improving the representation of groundwater resources in the model, in part because a prior study by the same group using CALVIN identified the use of groundwater recharge as a potential important climate change adaptation option.

Groundwater represents a large source of potential storage for water that could alleviate the year-to-year variability of precipitation that may increase in the future. In California, groundwater contributes about one-half of the current water supplies for human use or consumption.[59]

Researchers with Conservation International, UC Santa Barbara, UC Davis, Stanford University, and some foreign research institutions are developing a new dynamic ecological model for California. The final goal is to use the model to identify conservation strategies that would reduce the impact of climate change on biodiversity resources in the state.

The Center has commissioned ICF Consulting to develop preliminary estimates on the options available to reduce non-CO_2 GHGs in California. The "supply-curves," developed as part of this effort, identify how much and at what cost emission could be reduced with the implementation of different measures.

Planned projects include research on how to improve the estimation of non-CO_2 GHG emissions from key sources in California. For example, there are substantial uncertainties with the estimation of methane emissions from landfills, and current estimates are nothing more than order-of-magnitude estimates. This information is essential for the development of environmentally effective mitigation strategies.

Under joint funding from PIER and the U.S. Department of Energy, LLNL will be developing a new technology-rich model of the energy system in California for long-term analyses (up to 50 years into the future). The model will be used as part of a project designed to estimate the potential impacts to the electricity and natural gas systems of advanced energy pathways for California. For example, a hydrogen economy may rely on natural gas as a raw material for the generation of hydrogen. If this were the case, the natural gas system would experience increased demand, which in turn would affect California's electricity systems that depend heavily on this energy source.

Researchers associated with the Hydrologic Research Center in San Diego are developing a new short-term, seasonal hydrological forecast system, together with a decision-support system designed to improve the management of water reservoirs in Northern California.[90] This work is funded by CALFED Bay-Delta Program, the U.S. Bureau of Reclamation, NOAA, and the Energy Commission.

A previous study for the Folsom Reservoir demonstrated that such a system could increase hydropower production and reduce water losses while preserving flood control capabilities. The same forecasting and decision-support system was shown to substantially reduce the impacts of climate change for the climate scenario analyzed.[91]

Finally, under funding from NOAA and PIER and technical assistance from Energy Commission staff, researchers at Scripps conducted a series of studies designed to improve the management of energy resources making use of new probabilistic seasonal climate forecasting tools. For example, the results of one such study suggest that it may be possible to probabilistically forecast summer temperatures in the state using antecedent sea surface temperatures in the Pacific Northwest and the central Pacific Ocean region. The focus behind this research is to identify adaptation measures to climate variability now, so that they can be used in a timely manner if climate variability increases with climate change, as is expected to occur.

Carbon Sequestration

The Center is engaged in a series of projects designed to estimate the amount of carbon that could be sequestered in terrestrial ecosystems and geological formations in California.

In partnership with the California Department of Forestry (CDF), the Center is working with Winrock International to estimate the statewide baseline of carbon stocks in California lands and to estimate the potential to sequester carbon in existing forests, using different management practices or through forestation of range lands or other lands suitable for forests.

Study results indicate that the potential to sequester carbon is substantial and relatively inexpensive. Phase II of this work has started, with a more detailed analysis for Shasta County that will make use of a new data set to be collected using ground-level measurements and aerial laser-based measurements.

In close partnership with the California Department of Food and Agriculture (CDFA) and with additional funding by the Kearney Foundation, the Center commissioned a scoping study of the potential to sequester carbon in agricultural soils in the state. The scoping study was used to design a new research project that includes the enhancement and validation of agro-ecosystem models (Denitrification-Decomposition (DNDC) and Century) prior to their use for California studies.

Potentially, attention will be paid to nitrous oxide and methane emissions because the scoping study and other studies have found that not considering these gases may result in projects with actual net increases in GHG emissions (for example, nitrous oxide or methane emissions may more than offset the soil carbon gains). This project seeks to develop a realistic estimation of the potential to sequester carbon in California’s agricultural soils, including an understanding of what measures should be taken to entice the penetration of practices resulting in net sequestration by California farmers.

Finally, the California Energy Commission, with funding support from the U.S. Department of Energy (DOE), leads the West Coast Carbon Sequestration Partnership (WESTCARB). WESTCARB is conducting terrestrial carbon sequestration studies, similar to the one described above, on the other western states. In addition, WESTCARB has estimated the amount of carbon that could be sequestered in geological formations in the West Coast.

This amount includes an estimation of the costs and quantities that could be sequestered in marginal natural gas or oil fields in California, while at the same time increasing natural gas and oil production. The DOE has released a new request for proposals for phase II work. Phase II will include pilot demonstration projects for both terrestrial and geological sequestration.

The Economics of Climate Change

For the Center, researchers at UC Berkeley are significantly enhancing the DRAM model—a computable general equilibrium (CGE) model of the state economy—before they use the model for impacts and adaptation studies. A prototype version of the model is now available, and it is being used to estimate the potential impact of efforts designed to reduce in-state GHG emissions on the overall economy and different economic sectors. Future additions to the model include a proper representation of induced technology and the ability to model multiple regions in California.

Basic economic research is also being conducted to create the theoretical and empirical support needed for the enhancement of the CGE model discussed in the previous paragraph. Some examples of this work include basic research on the role that policies and regulations have in the development of new technologies.

For example, several studies (and experience) have pointed out that given the proper incentives, private industry can develop the technologies needed at considerably less cost than anticipated. How to include this feature in a credible way is an economic research frontier being pursued by Berkeley and several other groups. New econometric studies will also be conducted to improve the estimation of some of the key parameters needed for the CGE model.

Lawrence Berkeley National Laboratory has developed the first version of an energy balances database for the state (covering 1990 to 2001). An *energy balance* is simply a quantitative description of the energy flows in the state from extraction, transformation, and final consumption. The energy flows also include energy imports, exports, and storage. This work is being conducted because there are multiple sources of energy data and, in some cases, the data sources do not agree with each other.

The goal of this work is to enforce an accounting balance on the energy flows, thereby increasing the likelihood of producing more realistic energy statistics. The University of California, Berkeley, is using the data for the calibration of the CGE model discussed previously. Future activities include (among others) the collection of additional activity data such as building characteristics or industry profiles, so that researchers can perform decomposition analysis, which will increase understanding of the factors that affect energy consumption and GHG emissions, and will help explain existing trends.

Researchers at Berkeley are also conducting microeconomic analyses of water and energy consumption at the highest level of geographical disaggregation possible. They will combine these studies with urban growth models so that it will be possible to estimate future energy consumption based on scenarios of future urban expansion in California, through the framework of a geographical information system (GIS).

The work at Berkeley and through its affiliated researchers will evolve in the near future into an integrated economic assessment of mitigation, impacts, and adaptation studies on climate change for California. The results provided by other relevant PIER projects will be incorporated into the model. For example, carbon sequestration options in the agricultural sector will affect any modeled carbon market in the model, but at the same time enhance the economic performance of this sector in the model.

7. Staff Findings and Options for Policy

Climate change is already showing effects in California and its interlinked western region, and will likely grow to affect every sector of the California economy, directly or indirectly. California's human inhabitants should be able to adapt to climate change, but preliminary research is beginning to suggest that adaptation is likely to be costly.

For ecosystems, the situation is serious with climate change exacerbating already stressed ecosystems and, perhaps, negating some of the biodiversity benefits of large ecosystem conservation plans being implemented in the state. Further research is needed to better understand the potential impacts and adaptation measures that California should adopt in the face of the threats and opportunities that climate changes pose for the state.

More comprehensive observations, better model tools and model runs, and probabilistic climate change scenarios being developed by the Energy Commission should be a useful resource not only for research impact and adaptation analyses, but also for planning scenarios on state long-term planning efforts such as the State Water Plan and the Integrated Energy Policy Report.

The framework provided by these scenarios should help to produce much needed and better coordinated planning efforts, with a more consistent set of policy recommendations for the state. Thus, the state-funded applied research should be an essential part of the state's overall effort to reduce impacts and adapt to a changing climate.

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9. Acronyms

CALFED	CALFED Bay-Delta Program
CARB	California Air Resources Board
CDF	California Department of Forestry
CDFA	California Department of Food and Agriculture
CGE	computable general equilibrium model
CM	center of mass
CSIRO	Commonwealth Scientific and Industrial Research Organization
DNDC	Denitrification-Decomposition model
DOE	U.S. Department of Energy
DWR	Department of Water Resources
GHGs	greenhouse gases
GIS	geographical information system
GWh	gigawatthour
HADCM	Hadley Center Model
IIASA	International Institute for Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
IPSLCM	a French climate model
LFI	Levee Force Index
LLNL	Lawrence Livermore National Laboratory
MW	megawatts
NAS	National Academy of Science
NOAA	National Oceanic Atmospheric Administration
PCM	Parallel Climate Model
PG&E	Pacific Gas and Electric
PIER	Public Interest Energy Research
PM	particulate matter
RSM	Regional Spectral Model
SCAQMD	South Coast Air Quality Management District
TAR	Third Assessment Report
Tmax	maximum temperature
Tmin	minimum temperature
UC	University of California
WESTCARB	West Coast Carbon Sequestration Partnership